ADAFs, accretion discs and outbursts in compact binaries

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Abstract

I discuss the status of the Soft X-ray Transient model. First, I discuss and then compare with observations the assumption that the geometrically thin disc evaporates into an ADAF. Second, I address the problems created by the recent determinations of the distance to SS Cyg, according to which the Disc Instability Model does not apply to this famous dwarf-nova, thus casting doubt on the application of this model to any system at all.

Key words: Advection Dominated Accretion Flows, Accretion discs, Low-Mass X-ray Binaries, Dwarf Novae, 1H 1905+000, SS Cyg
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1. Introduction

As shown by Dubus et al. (2001) the disc instability model (DIM, see Lasota, 2001, for a review) of Soft X-ray Transients (SXTs) must take into account disc truncation and X-ray irradiation. Irradiation is clearly observed in persistent systems (i.e. in Neutrons-Star (NS) SXTs since all Black-Hole (BH) SXTs, are transient) and though it had often been ignored or incorrectly described (see Dubus et al., 1999, for the correct description) its effects on the disc structure in general and outbursts in particular are now universally accepted and non-controversial. Disc truncation has a different status. Although it is usually accepted that in low accretion-rate states discs are truncated (the famous Fig. 1 in Esin et al., 1997, is now used as the standard representation of the disc structure), the reasons usually given are spectral or timing-based. The fact that without truncation it is impossible to get outburst cycles resembling the observed ones (as shown e.g. by Menou et al., 2000; Dubus et al., 2001) is totally ignored even in the best reviews of the subject (e.g. Done et al., 2007).

The reason for truncation is twofold. First, it is needed to get very long recurrence times without playing games with the viscosity parameter α. Second, for non-truncated discs the DIM predicts ridiculously low accretion rates onto the compact object, rates that are clearly contradicted by X-ray observations of quiescent SXTs (see e.g. Lasota, 1996; Lasota et al., 1996; Hameury et al., 2003). This reason can be easily bypassed. α is too simple a parameter to describe the wealth of phenomena in accretion discs, and in the standard DIM two values of this parameter (different for cold and hot discs) must be used anyway.

The second reason, however, is impossible to evade (though not for lack of trying). The idea behind the attempts at evading the low accretion-rate restriction is very simple: if the X-rays in quiescence are not accretion-generated then there are no constraints on the accretion rate. The origin of quiescent X-rays had been attributed both to the companion (Bildsten & Rutledge, 2000) and the disc (except for the hot spot not much is left

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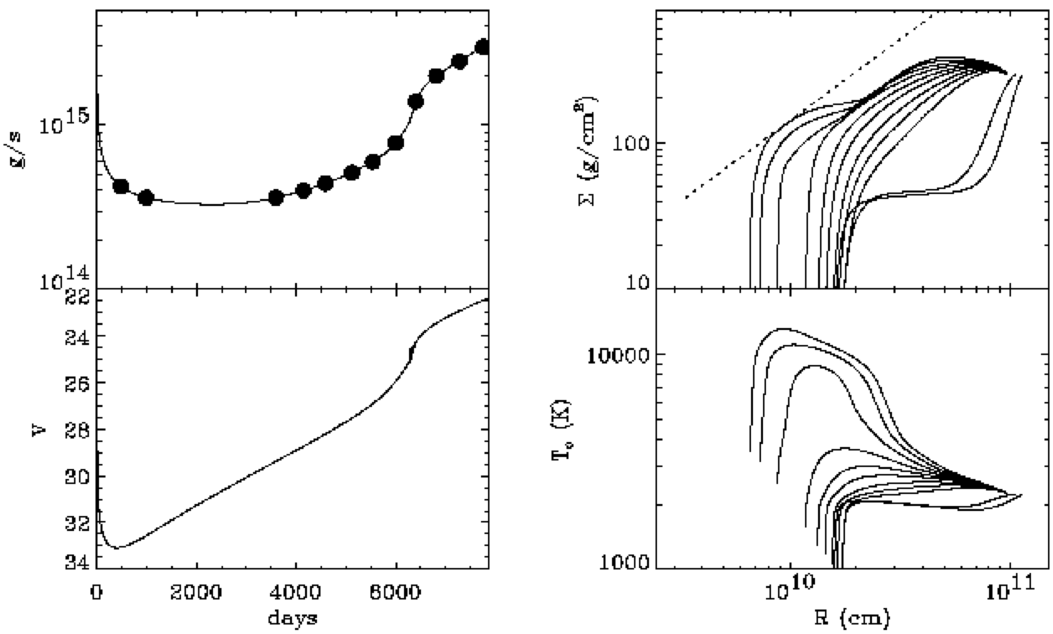

Fig. 1. Quiescence for one of the models discussed in Dubus et al. (2001). The four panels show: the accretion rate $\dot{M}_{\rm in}$ onto the black hole ($M_{\rm BH} = 7{\rm M}_\odot$, the V magnitude and the surface density and temperature profiles. The disc is truncated by "evaporation". The mass transfer from the secondary is slow enough for matter to diffuse down the disc, gradually increasing $\dot{M}_{\rm in}$ and decreasing $R_{\rm in}$. The outburst is triggered at $R \approx 10^{10}$ cm when Σ reaches $\Sigma_{\rm max}$ (dotted line). The lower densities at the beginning of the quiescent state are due to the irradiation-controlled outburst decay. During the quiescence most of the surface-density profile is roughly parallel to the critical one $\sim R^{1.11}$.

anyway) when they could not be ascribed to the compact object, i.e. in the case of BH SXTs. It was quickly demonstrated that the companion star cannot be the source of X-rays in quiescence (Lasota, 2000; Narayan et al., 2002). The disc origin of X-rays (Nayakshin & Svensson, 2001) generated less interest. Presumably the main reason was that a similar (in fact identical) problem is encountered when applying the DIM to dwarf nova outbursts. There too the X-ray luminosity is well above the level predicted by the model, but in eclipsing systems the X-ray source is clearly seen to be located near the white-dwarf. The size of this source is no bigger than that of the white dwarf. Clearly it is not the accretion disc. Of course one could argue that (truncated) discs around black holes are totally different from CV discs, and in addition to playing with α one could make them radiate in X-rays; but such a solution is not very compelling. Astrophysicists, in contrast to cosmologists and (post-modern) theoretical physicists, usually adopt the ontological parsimony of William of Ockham.

Although disc truncation is controversial (and its physics not totally understood) it is almost universally agreed that the mechanism responsible for SXT outbursts is described basically by the same DIM that is used to describe dwarf-nova outbursts. Only the effects of X-ray irradiation of the outer disc have to be added to this model to make it work for SXTs. Truncation is the common feature of both variants of the model. For example Schreiber et al. (2003) showed that the multi-wavelength properties of the outburst cycle of the dwarf-nova SS Cyg are best reproduced by the DIM with a truncated inner disc. However, according to recent distance determinations the DIM should not apply to SS Cyg because it is not a dwarf nova. I will discuss this problem (following Schreiber & Lasota, 2007) in Sect. 3, after addressing the question of the "faint black-hole" paradigm.

2. Are accreting black holes fainter than accreting neutron stars?

The existence of truncated quiescent discs leads to several problems. First, that of the truncation mechanism. In the case of white dwarfs and neutron stars the discs can be truncated by the magnetic fields of the accreting objects. Systems in which this is the case are well known: polars (which truncate discs to nonexistence), intermediate polars and of course accreting pulsars. In the case of systems which have low states (and of discs in the high state) no direct evidence is available for the moment but the circumstantial evidence is pretty strong for VY Scl stars (Hameury & Lasota, 2002, 2005) and Aql X-1 (Casella et al., 2007). However, astrophysical black holes being devoid of their own magnetic fields, disc truncation must be attributed to a different mechanism (which could also work for some white dwarf and neutron star systems). This mechanism, usually called "disc evaporation", still escapes our understanding despite some interesting contributions (e.g. Meyer-Hofmeister & Meyer, 2003).

The second problem concerns the form of the accretion flow beneath the truncation radius. The simplest and oldest model is that of ADAF (Narayan et al., 1996; Lasota et al., 1996). But there are many other possibilities (Blandford & Begelman, 1999, but see Abramowicz et al. (2000)) and there is now evidence that quiescent BH SXTs produce jets (Gallo et al., 2006) so it is possible that a substantial part of the accretion flow does not cross the horizon but is ejected from the system (possible but not necessary if jets are produced at the cost of the black hole's rotational energy as in the Blanford-Znajek mechanism). Mixed models (ADAF + jet) were therefore suggested (see e.g. Yuan et al., 2005). One should remember here that even in the case of a "pure" ADAF (no outflow) the thermal energy advected into the black hole can be (in principle) negligible (Paczyński, 1998, and Fig. 2 in Chen et al. (1997)).

The ADAF solution applied to both accreting black holes and neutron stars has one immediate consequence: neutron stars should be brighter because all the thermal energy that was not radiated away from the accretion flow will have to be emitted from the stellar surface. However, one should *not* deduce from this that any quiescent black-hole binary system will be fainter than any neutron-star binary in a similar state of activity. The "faint black-hole paradigm" is supposed to apply only to compact bodies accreting at the *same* rate. In Lasota (2007) I recalled the brief and unfinished story of testing the "faint black-hole paradigm". Here I will discuss in more detail the method (Lasota & Hameury, 1998; Menou et al., 1999b) of attempting to make sure that the BH and NS SXTs under comparison have comparable accretion rates.

The idea is to plot the quiescent luminosity as a function of the orbital period (Fig. 2). Contrary to naive expectations, this method does *not* assume that BH SXTs and NS SXTs have the same transfer rates at a given orbital period. It is based on the assumption that the truncation radius where the transition from disc to ADAF occurs is roughly a constant fraction of the circularization radius (Menou et al., 1999b,a; Lasota, 2000)

$$R_{\rm tr} = f R_{\rm circ}(M_1, q, P_{\rm orb}), \quad f \lesssim 0.48, \tag{1}$$

q being the mass ratio (secondary/primary), M_1 the primary mass, and the value of 0.48 coming from the requirement that the inner disc radius must be no smaller than the impact distance of the mass-transfer stream.

The accretion-rate profiles in a quiescent disc are roughly parallel to the critical one $\dot M_{\rm crit} \sim R^{2.68}$, but close to the outer disc edge they flatten to match the mass-transfer rate(see e.g. Fig. 1). Truncating the disc at radius given by Eq. (1) determines an accretion rate which is independent of the mass-transfer rate. The resulting accretion rate will depend on M_1 and q but this would make the ratio between the NS and BH SXT accretion rates differ by a factor 2 - 4 and not by more than an order of magnitude, as observed. In fact on Fig. 1 one could attribute to the luminosities, as a function of period, a slope of roughly 1.7 – 1.8, as expected from the slope of the $\dot M_{\rm crit}(R)$ relation (see Hameury et al., 2003).

One can compare the assumptions described above with models of SXT outburst cycles by Dubus et al. (2001). Figure 1 shows the quiescent phase of a BH SXT outburst cycle. The right panels represent a dozen surface density Σ (upper panel) and central temperature T_c (lower panel) profiles of a quiescent accretion disc around a black hole. Dots on the "light-curve" (upper-left panel) show where the "snapshots" were taken. Except for the first two (just after the end of the outburst) and the last two (just before the next outburst) profiles, the surface-density profiles are roughly parallel to the critical-density lines (in fact they are slightly shallower). During $\sim$ 20 years the inner radius moves

in by a factor $\sim$ 3 but until the last $\sim$ 3 years the accretion rate does not vary by more than a factor of 2. This reflects the "self-similar" way the disc fills up. Dubus et al. (2001) discuss the dependence of the outburst cycle properties on the mass of the compact object. Although, as mentioned above, there is some M_1 dependence in the critical values of density (accretion rate), the strongest mass-dependence enters into the model trough the formula describing the disc truncation, i.e. the disc "evaporation", because $\dot{M}_{\rm evap} \sim M_1^3$. As a result, in quiescence, the disc around a lower-mass compact object is truncated at smaller radii, which reduces the inner accretion rate. This effect would therefore reduce the ratio of neutron-star to black-hole quiescent luminosities. Of course one should keep in mind that the evaporation prescription used here is not based on any physical mechanism but other physically motivated approaches are not easily used in full irradiated-disc outburst calculations (as discussed in Dubus et al., 2001).

One can conclude that testing the faint black hole paradigm by comparing quiescent NS and BH SXTs at similar orbital periods is a reasonable procedure (and in any case the only one that makes sense).

2.1. *The case of 1H 1905+000*

Recently Jonker et al. (2006, 2007) found that the neutron-star soft Xray transient 1H 1905+000 could be the spoilsport long-awaited by the anti-ADAF crowd. Its quiescent X-ray luminosity is at most $\sim 1 \times 10^{30}$ erg s^{-1}. Jonker et al. (2007) notice that "this luminosity limit is lower than the luminosity of A0620-00, the weakest black hole soft X-ray transient in quiescence reported so far", which is a true statement. However, the conclusion that "the claim that there is evidence for the presence of a black hole event horizon on the basis of a lower quiescent luminosity for black holes than for neutron stars is unproven" is not. After the publication of the first upper limit in Jonker et al. (2006) I addressed this point in Lasota (2007), explaining in detail why the faintness of the neutron star in 1H 1905+000 does not invalidate the fainter black hole paradigm. However, since my discussion was overlooked by Jonker et al. (2007, but see Cornelisse et al. (2007)), I think it will be useful to repeat the argument in slightly different form, using formulae freshly calculated for helium discs in Lasota et al. (2008).

I will use Fig. 2 which the same as Fig. 1 in Lasota (2007) but with a modified position of 1H 1905+000. As before, the orbital period of 1H 1905+000 is unknown but it is certainly very short (Jonker et al., 2007). I have therefore tentatively assumed a period of 1 h, but even a longer period would not contradict the claim that black-hole systems are fainter than those harbouring neutron stars (no black-hole low-mass X-ray binary has been observed with an orbital period $\lesssim 4$ hr).

Even if the actual quiescent X-ray luminosity of 1H 1905+000 were much lower than the *Chandra* upper limit it would not necessarily be a problem for the black-hole faintness paradigm. This is because 1H 1905+000 is a rather unusual binary. The faintness of the secondary implies an ultra-compact X-ray binary (UCXB), in which case the neutron star companion would be a low-mass helium or carbon-oxygen white dwarf (Nelemans et al., 2004). When transient (very short-period systems are rather persistent Deloye & Bildsten, 2003), such compact binaries exhibit short ($\gtrsim 10$ – $\gtrsim 100$ days), exponentially decaying outbursts, as expected from small, X-ray irradiated accretion discs (Dubus et al., 2001). In all these very compact transient systems the neutron star is a millisecond pulsar (MSP). Both their outburst (usually a few % of the Eddington luminosity) and quiescent X-ray luminosities ($< 10^{32}$ erg s^{-1}) are lower than those observed in longer period SXTs (Campana et al., 2005). This might seem to be similar to 1H 1905+000 whose outburst luminosity was $\sim 4 \times 10^{36}$ erg s^{-1}. However, the outburst behaviour of this system is totally different from that observed in other short-period binaries and UCXBs. Instead of short outbursts 1H 1905+000 exhibited one $\gtrsim 10$ year long outburst that ended in the late 1980s or early 1990s. Since then it has been quiet. It is not clear why 1H 1905+000 is so different. During 11 years, say, it accreted $\sim 8 \times 10^{24}$ g. This is a lot, but a helium accretion disc can contain as much as

$$M_{\rm D,max} \approx 3.5\ \times 10^{25} \left(\frac{\alpha_{\rm cold}}{0.01}\right)^{-0.83} \times \left(\frac{M_{\rm ns}}{1.4 {\rm M}_\odot}\right)^{0.67} \left(\frac{P_{\rm orb}}{1{\rm h}}\right)^{2.13} \ {\rm g}, \qquad (2)$$

where $\alpha_{\rm cold}$ is the cold-disc viscosity parameter and $P_{\rm orb}$ the orbital period. I used the helium-disc critical surface density from Lasota et al. (2008). For the disc radius I took:

$$\frac{r_{\rm D}({\rm max})}{a} = \frac{0.60}{1+q}, \qquad (3)$$

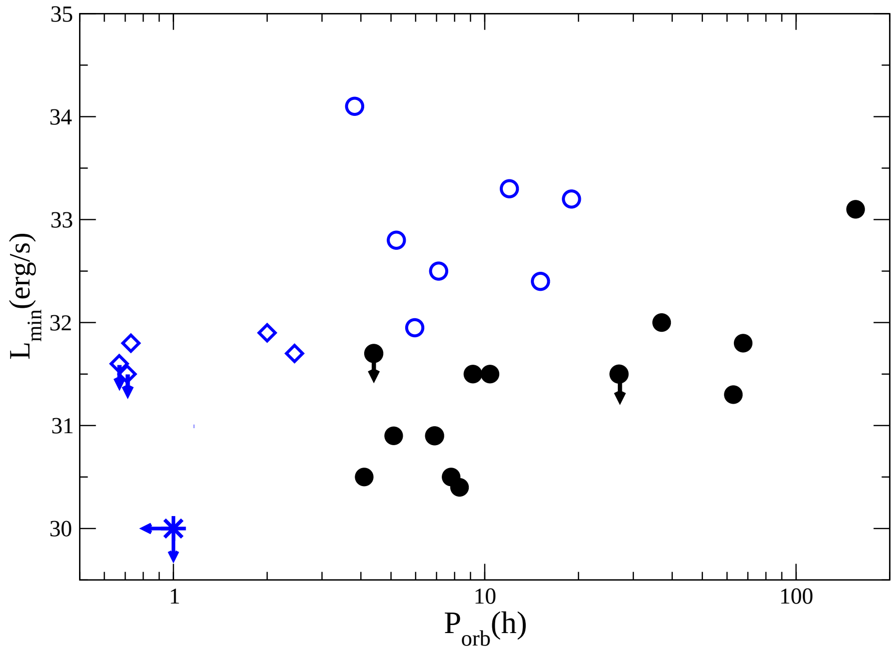

Fig. 2. Quiescent luminosities of black holes (filled circles) and neutron star (open circles and open diamonds) soft X-ray transients. Diamonds correspond to accreting millisecond pulsars. The star represents the system 1H 1905+000 whose orbital period is unknown but all the available evidence suggests it is a UCXBs (see the text). This figure shows that in quiescent transient LMXBs, *at a given orbital period*, neutron stars are brighter than black holes. Data for black holes from Garcia (private communication), for neutron stars from Campana et al. (2005).

(valid for $0.03 < q < 1$, Paczyński, 1977), where

$$a = 2.28 \times 10^9 M_1^{1/3}(1+q)^{1/3} P_{\rm min}^{2/3}\,{\rm cm} \tag{4}$$

is the binary separation; $P_{\rm min}$ being the orbital period in minutes. In Eq. (2) $r_{\rm D} = 0.6\,a$

The maximum outburst luminosity for an irradiated helium disc around a 1.4 $M_\odot$ neutron star can be estimated as

$$L_{\rm max} \simeq 3.5 \times 10^{37} \left(\frac{P_{\rm orb}}{1{\rm h}}\right)^{1.67} {\rm erg\ s^{-1}}, \tag{5}$$

(Lasota et al., 2008). Therefore 1H 1905+000 could in principle be a "normal", short-duration X-ray transient source, but it isn't. Maybe its long "outburst" was due to irradiations of the secondary. If its period is ~ 20 min it could be marginally stable with respect to the thermal-viscous instability in an irradiated helium (or carbon-oxygen) accretion disc.

Another possibility is that the companion star stopped transferring mass. In such a case, after a short time, the neutron star would cease accreting at all. It is perhaps worth repeating that in such a case the *accretion* luminosity of the neutron star will certainly be lower than the luminosity of any accreting black hole. Then the absence of X-rays is a problem for Brown et al. (1998) but not for me or other ADAF-advocates. Such a scenario is quite realistic. After all there exist CVs which do exactly that: some VY Scl stars stop transferring mass for years after being for years among the brightest CVs. We don't know why but they do. These strangely behaving companion stars are K-M dwarfs (close to being fully convective) while the secondary of 1H 1905+000 is most probably a helium or C/O star, but this should not prevent them from arresting mass transfer.

The considerations above assume that the binary systems in question have a *bona fide* structure of a LMXB: matter flowing from the L_1 point forms a disc through which it is accreted onto the compact object. However, the form of mass-transfer in systems with such very low mass ratios has not been studied and only some general properties of such systems can be conjectured (Dubus, private communication). For values of $q \lesssim 0.02$ the circularization radius becomes larger than the estimates of the outer radius Eq. (3). Most probably matter streaming in from the companion circularizes onto unstable orbits. For $q \approx 0.02$, matter is added at $R_{\rm circ}$ onto orbits that can become eccentric due to the 3:1 resonance. For $q \approx 0.005$ the circularization radius

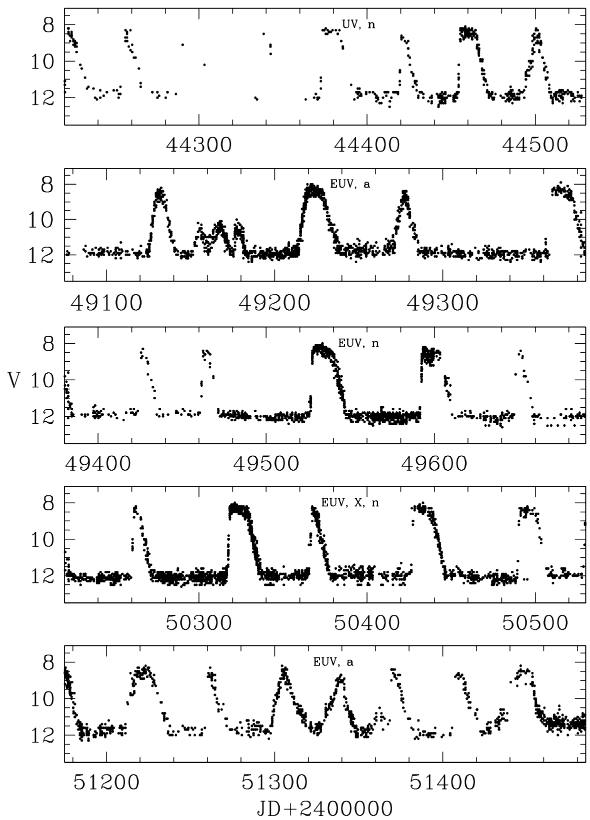

Fig. 3. Examples of the visual light curve of SS Cyg. Outbursts called normal are marked with "n" and so-called anomalous outbursts are designated by "a". SS Cyg is also a UV, EUV, and X-ray emitter. The data are from the AFOEV, the figure from Schreiber et al. (2003).

approaches the 2:1 Lindblad resonance. This might efficiently prevent mass being transferred onto the compact object.

Nota bene, equivalent systems with a black-hole instead of a neutron star would have a minuscule mass ratio < 0.01 ($M_{\rm bh} > 4{\rm M}_{\odot}$). It is probably not a coincidence that there are no observed black-hole counterparts of neutron-star X-ray binary systems at orbital periods shorter than 2 hours (it is not certain if this could explain the lack of observed BH LMXBs below 4 hours, though). Evolutionary models suggest that such systems should exist (Yungelson et al., 2006). If they do, they are not your normal LMXBs.

Although I agree with Danny Steeghs (private communication) that "there is always something [to be said] for at least trying to kick paradigms and see if they fall over", I think the 1H 1905+000 kick is too weak even to shake the faint black hole paradigm. But observers should of course keep trying.

3. Does the thermal-viscous instability model describe dwarf-nova outbursts?

SS Cyg is the brightest and best observed dwarf nova in the sky (see Fig 3). It therefore came as a shock when its distance (reputed until then to be $\sim$ 100 pc) was announced to be 166 ± 12 pc after the determination of the HST/FGS parallax of this system (Harrison et al., 1999). It was immediately noticed that at such a distance the mass-transfer rate would be well above the critical one and as a consequence, according to the DIM, SS Cyg should not be a dwarf-nova contrary to observational evidence. Schreiber & Gänsicke (2002) analyzed the consequences of this drastic distance revision and came at the conclusion that if we want to avoid a substantial revision of the model we must either assume an important enhancement of the mass transfer during the outburst (which would in fact be a substantial revision of the model anyway) or bring back the distance close to the previous value. This latter choice was probably that of the majority, at least of those who noticed the problem. However, recently Bitner et al. (2007) re-determined the parameters of SS Cyg and arrived at the conclusion that they are consistent with a distance $\gtrsim 140 - 166$ pc supporting the parallax measurement. This independent confirmation of the large distance to SS Cyg triggered a new re-evaluation of the validity of the DIM (Schreiber & Lasota, 2007).

First we confirmed that at a distance $\gtrsim$ 140pc the mass-transfer rate of SS Cyg is in contradiction with the DIM. However, we also pointed out that the problem is more serious than the failure of the DIM. In fact we know from observations of disc accretion in CVs that below a certain mass-transfer rate their discs go into outburst, producing dwarf novae. At higher mass transfer rates, the disc is stationary and the corresponding class of CVs form the nova-like systems. In agreement with this picture, the mean absolute magnitudes of dwarf novae have been found to be lower than those of nova-like systems (see Warner, 1995, Fig. 9.8). To check whether this agreement remains valid for a distance to SS Cyg of 166 ± 12 pc, we compared the mean mass transfer rate derived for SS Cyg with that obtained for a set of well-observed nova-like systems and three dwarf novae with measured HST/FGS parallax (see Tables 2 and 3 in Schreiber & Lasota, 2007).

Fig 4 (inspired by Fig 1 in Smak, 1983, who was the first to attempt such a test) shows the derived

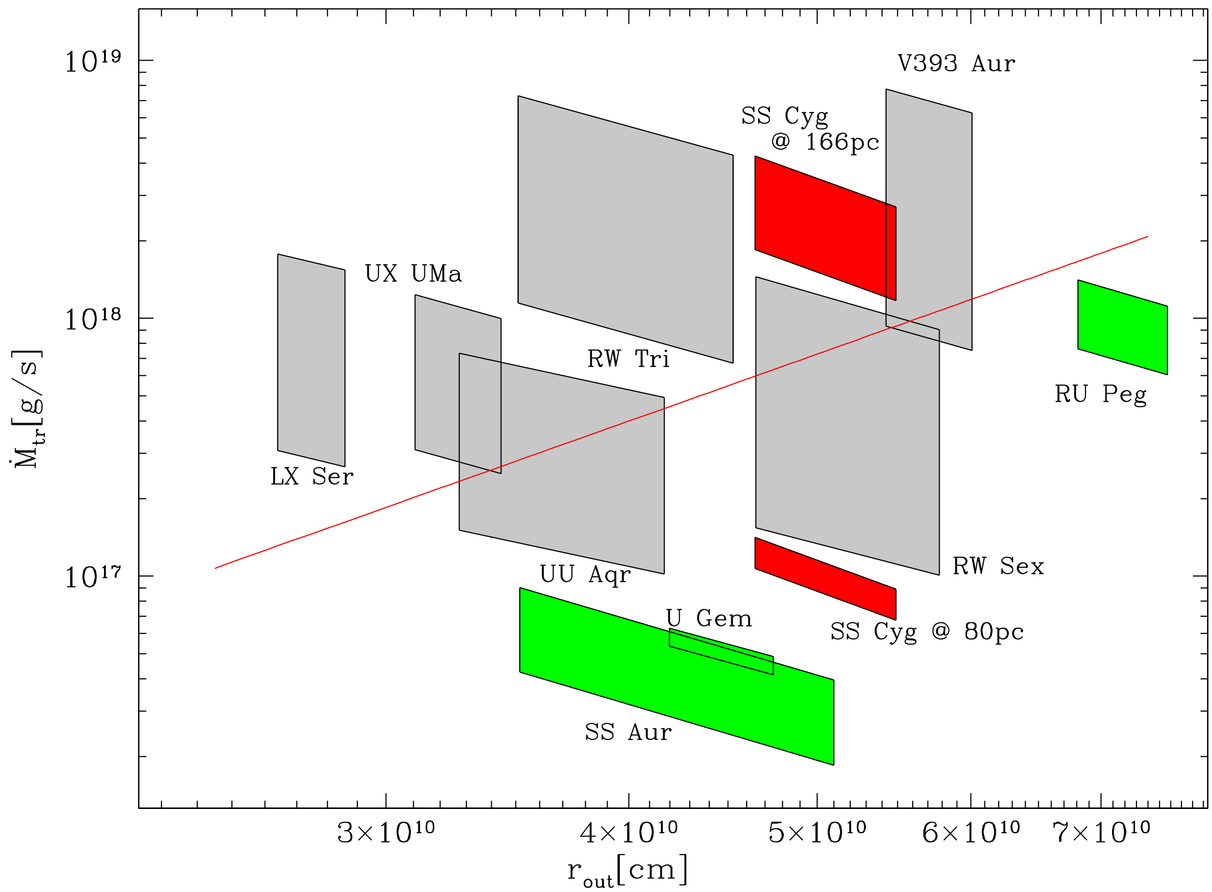

Fig. 4. The mean mass transfer rate of SS Cyg and of six well known nova-like CVs as a function of the outer radius of the disc during outburst. As the binary parameter of SS Cyg the values (and uncertainties) derived by Bitner et al. (2007) were used. Both, in order to make the plot easier to read and because the broad ranges of possible parameters do not represent well-determined values with certain errors, we use shaded boxes instead of error bars. The solid line represents the critical mass transfer rate. According to the DIM, this line should separate dwarf novae and nova-like systems. On the other hand SS Cyg should be stationary, being brighter than (or as bright as) nova-like systems (for details see Schreiber & Lasota, 2007).

mean mass transfer rates as a function of the outer radius of the disc during outburst. To avoid our results depending on uncertainties in the system parameter derived from observation, we used rather broad ranges of parameters. The straight line represents the critical mass transfer rate for $_1 = 1\mathrm{M}_{\odot}$. Obviously, at a distance of 166 pc the mean mass transfer rate of SS Cyg is above this limit, as mentioned above. The other three dwarf novae are below the dividing line and the nova-like stars have mass transfer rates higher than (or similar to) the critical rate. The striking point of Fig. 4 is the fact that the mean mass transfer rate of SS Cyg is higher than (or as high) as those derived for nova-like systems with similar system parameters. Therefore if SS Cyg is indeed $d \gtrsim 140$ pc away, the difference between nova-like systems and the dwarf nova SS Cyg cannot be attributed to the mean mass transfer rate. This conclusion obviously contradicts the generally accepted picture of accretion discs in CVs, not only the DIM.

Clearly, one could argue that the distances to the nova-like systems are systematically too small. However, the distance to RW Tri is based on a HST/FGS parallax and for the other systems we used very large upper limits for the distance. Hence there is no easy way out of the problem. A non-easy way is to assume that SS Cyg outbursts are triggered by mass transfer enhancements. These enhancements would have to be so serious that this would be equivalent to getting back to the old universally rejected mass-transfer instability model. This in itself would not be a problem (at least not for me). The problem would be to explain why SS Cyg is does this while its neighbours (in period and spectral type) do not. What is

so special about SS Cyg? Since this is a place where I can express my personal feelings I will admit that I believe that finally it will be established that the true distance is $\sim 100\,\mathrm{pc}$.

In the case of SXTs there was a similar problem with GRO J1655-40. At first it was thought to transfer mass at a rate too high for it to be transient. Various attempts to circumvent this problem were made but it was the revision of the parameters of this binary by Beer & Podsiadlowski (2002) that solved the problem. Now we hear that GRO J1655-40 is much closer than previously thought and this would reduce the mass-transfer even more. But, paradoxically, if we were one were to accept the distance proposed by Foellmi et al. (2006), the secondary in GRO J1655-40 would not be filling its Roche-lobe and in this case too we would have to invoke a mass-transfer instability to explain the outbursts. [1]

4. Conclusion

Of the two pillars of the SXT–outburst model, the ADAF one is making quite a good job at resisting attempts to topple it. The other one, the DIM, is in danger of falling if the larger distance to SS Cyg is to be taken seriously. If the DIM were to be completed by a contribution from enhanced mass-transfer from the secondary I would be the last to be surprised (see e.g. Lasota, 1996, 1997).

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[1] It is rather unlikely that the secondary in GRO J1655-40 is not filling its Roche-lobe but the mass-transfer enhancement still might contribute to the outburst properties (see Esin et al., 2000).

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